

DEVELOPMENT OF A CRASHWORTHY SYSTEM: INTERACTION BETWEEN CAR STRUCTURAL INTEGRITY, RESTRAINT SYSTEMS AND GUARDRAILS

Anders Ydenius, Folksam Research, Sweden

Anders Kullgren, Folksam Research, Sweden

Claes Tingvall Swedish National Road Administration and Monash University, Australia

Paper number:171

ABSTRACT

In the development of a crashworthy road transport system, guard-rails could play an important role in preventing frontal collisions on roads without separated lanes and in avoiding collisions with roadside objects. Crash pulses in crashes into guard rails may differ from e.g. car-to-car collisions, concerning the duration and mean acceleration. If the characteristics of crash pulses into guard-rails differ from those used in the design of vehicle interior restraint systems, it may influence the performance of these systems.. Collisions with soft guardrails, such as wire ropes, may often have pulse duration of 200 ms or more. The performance of e.g. airbag systems in collisions with such duration is rarely studied.

This study presents the results of six crash tests, carried out with identical vehicles running into three types of guard rails at two different test speeds, 80 and 110 km/h, and at two different impact angles, 45° and 20° respectively. The three tested guard-rails were: a flexible barrier - a wire rope, a semi-rigid barrier - a W-beam guard rail and a rigid type - the concrete barrier. The characteristics of these types of guardrails were found to vary a lot concerning the transferred crash severity and physical behavior. The airbags did not deploy in either of the two wire-rope tests, whereas they deployed in the tests with concrete barriers and W-beam barriers at 45°, 80 km/h. Severe car deformations occurred in the 45°, 80 km/h test with the concrete barrier, while no interior deformation occurred in the wire rope and W-beam tests. The tests demonstrated the wide range of crash behavior with different barriers and guard-rails. Furthermore they demonstrated the importance of choosing the right barrier for a particular need in road construction.

INTRODUCTION

In 1997 the Swedish Government proposed a new strategy for the road traffic safety, called "Vision Zero" (Tingvall, Lie 1996). The goal of the strategy is no fatalities or long-term disabilities in the road-traffic system (Kommunikationsdepartementet 1997). The Swedish vision is based on a level of the mechanical force that the human body can tolerate

without being killed or seriously injured. The goal sets new demands on the responsible authorities of the road traffic system. Road designers should know how the vehicles can protect their occupants and car manufacturers should know how the infrastructure is built to be able to assess the level of violence the roadside objects may transfer to the vehicles at a given speed limit in case of a collision. The injury tolerance limits for the vehicle occupants constitute an essential part of the design of such a system.

For decades big efforts have been made to reduce the injury risk in passenger cars. The efforts have mainly been focused on the passive safety of the vehicle, such as introducing various safety systems and improving the crashworthiness through continuous improvements in the vehicle structure. The development of the design of roadside objects has also considered safety. However, road constructors have so far only to a minor extent, used the input from the vehicle research industry in the design and development of road-side objects.

To achieve progress in a crashworthy road traffic system, different types of guardrails are more commonly used to avoid vehicles either running off the road or reaching opposite driving lanes. The general purpose with most guard-rails is to avoid hazard objects and redirect the vehicle. The guard-rail itself may, however, cause such a high severity of the crash that the vehicle will not be able to handle it without exceeding the limits causing occupant injuries.

The present paper describes the results of a series of tests with different guard rails with the aim to study the interaction between the car structural integrity, restraint systems and guard rails. The speeds and angles were chosen to represent worst case in terms of angles and speed at two types of roads.

MATERIAL AND METHOD

The results presented in this paper are conducted from six crash tests (see Table 1) with three different types of barrier (see Figures 1-3). The barriers were mounted on a paved airfield.

The tests, conducted by Monash University in Australia, were financed by several Swedish and Australian bodies.

Barrier types

Figure 1 shows a rigid concrete barrier, which was fastened to the ground. The concrete barrier consists of six pre-cast concrete sections, 6,2 m each, 700mm wide in base, total height 800mm. The wire-rope barrier in Figure 2 consists of four wires with two lower wires wrapped around the posts and two straight wires on the top of the posts. The distance between the posts was 2,5 m. The W-beam barrier in Figure 3 is a steel barrier with U-section posts 2,5 m apart.

The test series were conducted at two crash angles. The angles between the barrier line and driving line were 20° and 45° and the selected test speeds were 110 and 80km/h respectively. The 45° -angle test was chosen as the worst possible case situation on a road with two or more driving lanes. The boundary exit angles are defined in NCHRP R350, (National Cooperative Highway Research Program report 350). The 20 degree angle test should represent worst case on a 4 lane highway.

Testvehicle

The test vehicle in all tests was Toyota Yaris (Echo) model year 2000, equipped with a driver airbag and front seat belt pretensioner. Toyota Yaris has been rated four stars in Euro NCAP and represents a relatively small vehicle with modern design.



Figure 1. Concrete barrier.



Figure 2. Wire-rope barrier.



Figure 3. W-beam barrier.

The purpose with the vehicle's size class was to choose a small vehicle, yet safe for its class, because this vehicle size class is less likely to get a good result, compared to a larger vehicle class. The test vehicles (Figure 6) were equipped with a special steering-wheel system and were, as well as the throttle, wireless controlled from outside the car. The speed was projected into an on-board camera viewing the area ahead of the car and visualized by a virtual reality visor outside the vehicle.

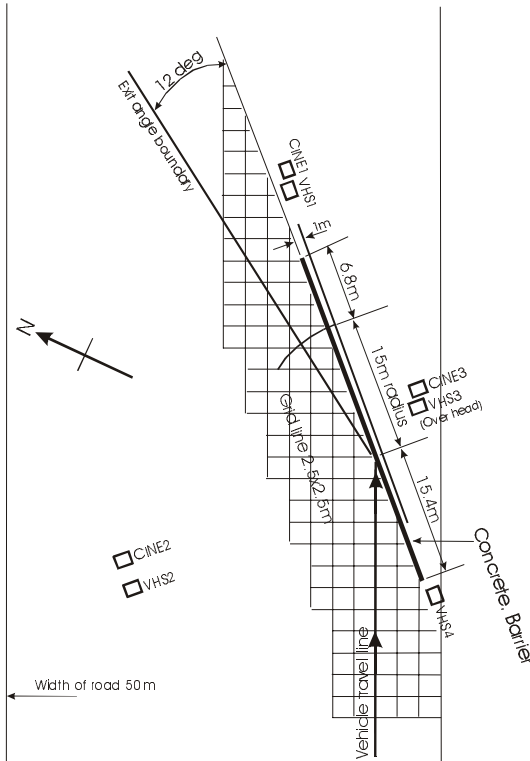


Figure 4. Test track setup 20°/110km/h.

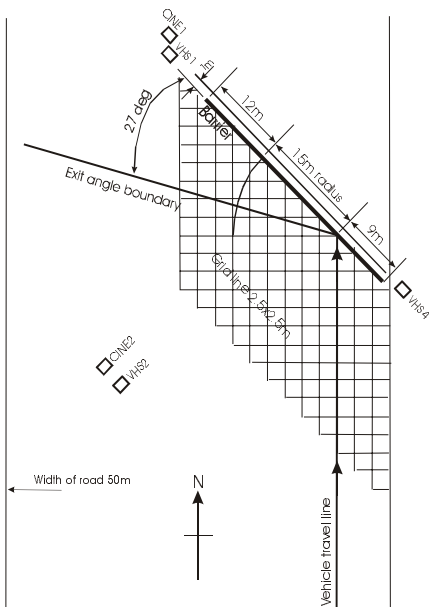


Figure 5. Test track setup 45°/ 85 km/h.



Figure 6. Testvehicle.

Table 1.
Test matrix

Test No	Impact Speed (km/h)	Impact Angle (°)	Barrier type
1	80	45	Concrete
2	80	45	Wire rope
3	110	20	Wire rope
4	80	45	W-beam
5	110	20	W-beam
6	110	20	Concrete

Instrumentation

On the driver's side a Hybrid III dummy was used, instrumented with Head (x, y, z) and Chest (x, y, z) accelerometers. On the passenger's side an uninstrumented Hybrid III was used.

Vehicle acceleration was measured with (x, y, z) accelerometers in the mid-section and rear part of the vehicle. Acceleration in x-direction was also measured on both sides and in the front part of the vehicle, see Figure 7.

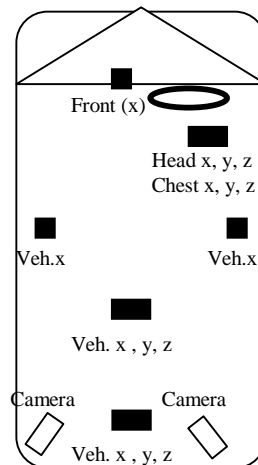


Figure 7. Vehicle instrumentation.

Two onboard cameras were mounted in every test vehicle. They were positioned so that it was possible to study the kinematics of the dummies and the deployment of the airbag and seatbelt pretensioners.

RESULT

Table 2 shows that the concrete barrier is sensitive to impact angles. At the concrete barrier impact angle of 20°, the vehicle acceleration peak value in the x-direction was 12g. The 20°-angle tests have a relatively small velocity vector, perpendicular to the barrier. In the same test the head resultant was 90g and the moderate HIC value was 330. In the 20°-angle test with the W-beam barrier no vehicle acceleration measurement was available. The dummy readings were low, indicating a low crash severity. The lowest vehicle deceleration occurred in the 20°-angle test with the wire-rope barrier.

The vehicle peak acceleration in the 45°/80 km/h test, see Table 2, was 32g with the stiff concrete barrier, 18g with the W-beam barrier and 7g with the flexible wire rope-barrier. The concrete barrier also caused a high HIC value, (1465) in the 45°-angle test.

Table 2.
Vehicle and dummy crash data

	Vehicle x-dir.	Vehicle resultant	Head resultant	HIC
Concrete 80 km/h, 45°	32g	45g	190g	1465
W-barrier 80km/h, 45°	18g	20g	-	<100
Wire-rope 80 km/h, 45°	7g	7g	13g	<100
Concrete 110 km/h, 20°	12g	18g	90g	330
W-barrier 110 km/h, 20°	-	-	18g	<100
Wire-rope 110 km/h, 20°	4g	9g	18g	<100

The low vehicle acceleration in the wire-rope tests, especially with the 45°- impact angle, relates to the deflection of the barrier. Comparing the deflection of different barriers in Table 3 with the values in Table 2, it could be seen that the vehicle acceleration and dummy head value are strongly related to the deflection of the barrier. The concrete barrier had virtually no deflection, whereas the wire-rope barrier had a 3.5-m barrier deformation in the 45°-angle test. It is also obvious that smaller elasticity of the barrier leads to a higher exit speed as shown in Table 3.

The semi-rigid W-beam barrier and the flexible wire-rope absorbed approximately 2.5-3 times more kinetic energy than the concrete barrier. In the 45°-angle tests the concrete and wire-rope barriers fulfilled the exit boundary angle of 27°. The boundary angle is defined as 60% of the impact angle according to NCHRP R350 recommendation.

Table 3.
Dynamic barrier data 80 km/h-45 ° impact angle

	Concr. 80km/h	W-beam 80 km/h	Wire rope 80 km/h
Barrier deflection (m)	0	1,8	3,5
Impact speed (km/h)	81	78	82
Exit speed (km/h)	61-66	0	40
Delta v	20-25	78	42
Kinetic energy absorbed kJ	95	292	246

At the 20°- impact angle the concrete barrier absorbed about the same amount of energy (see Table 4) as at the 45°-impact angle. Both the W-beam and wire-rope absorbed about twice as much kinetic energy as the concrete barrier in the 20°-angle test. All three barrier types fulfilled the exit boundary limits of 12°.

Table 4.
Dynamic barrier data 110 km/h/20° impact angle

	Concrete 110 km/h	W-beam 110 km/h	Wire-rope 110 km/h
Barrier deflection (m)	0	0,5	1,0
Impact speed (km/h)	110	109	110
Exit speed (km/h)	100	88	90
Delta v	10	21	20
Kinetic energy absorbed kJ	101	198	192

As shown in the 45°-angle tests (see Table 5), the airbag and pretensioner deployed in impacts with the concrete and W-beam barriers. In the W-beam test, the deployment of the driver's airbag was delayed. Obviously the vehicle decelerations in this case were on the verge of decision: to deploy or not.

Table 5.
Restraint systems 80 km/h/45°

	Concrete 80 km/h	W-beam 80 km/h	Wire rope 80 km/h
Seat belt pretensioner fired	Yes	Yes	No
Airbag fired	Yes	Yes	No

In the 20°-angle tests there was only one impact with the concrete barrier where the airbag and pretensioner deployed (see Table 6).

Table 6.
Restraint systems 110 km/h/20°

	Concrete 110 km/h	W-beam 110 km/h	Wire-rope 110 km/h
Seat belt pretensioner fired	Yes	No	No
Airbag fired	Yes	No	No

Figures of the deformed vehicles, vehicle trajectory and barriers are presented in the Appendix.

DISCUSSION

It is difficult to achieve a crashworthy road transport system without the exchange of knowledge and experience between the road and vehicle designers. A substantial part of crashes with severe or fatal injuries (Malm et al 1999) occur in impacts with fixed objects or heavy vehicles. To fulfil the road users' demands regarding the accessibility and usability, you must either build a vehicle that is able to handle these impact situations or reduce the travel speed dramatically. Due to economical limitations, safe roads with double separated lanes in both directions will not be built to a high extent. Guard rails could be a solution for the problems of frontal crashes and single crashes into the road furniture. However, various characteristics of different barriers, as mentioned by Wayne (1993), increasingly require suitable barriers for certain situations.

In general, the guard rails have two purposes: to avoid crashes with rigid objects in the roadside area and to prevent collisions with opposite-directed vehicles. However, guard rails should not cause similar or worse situations than in case of no barriers. It means that the vehicle acceleration in a crash into a

barrier should be below a certain level to avoid injuries. The risk of climbing over the barrier should also be minimised.

There are some parameters that influence the decision of which type of guard rail is the most suitable in certain situations, highlighted by this crash test series. For example: barrier stiffness, post strength, post spacing, fence height, impact angle, impact speed, vehicle weight and a limited vehicle crash severity. These parameters have various combinations of restraints that could be used to optimise the characteristics of a barrier for a certain situation. Or, to make it simpler: the task for each situation is to optimise the barrier stiffness and deflection to an acceptable amount of violence transferred to the vehicle.

The rigid barriers have a high stiffness, which at most impact angles gives a moderate or no deflection. As shown in these tests, they have the ability to redirect the vehicle away from hazard areas and at slight impact angles (<20°) the perpendicular forces on the barrier are relatively small, which most likely leads to a moderate vehicle crash severity. If the expected impact angles are greater for example on a three-lane highway, the stiffness of the rigid barrier can be a disadvantage due to high vehicle crash severity levels. This situation is demonstrated in the 45°-angle test.

Flexible barriers give a longer duration for deceleration and thus a lower crash severity on the vehicle, which can be seen in the tests with wire-ropes. On the other hand, the deflection on the flexible barrier can be unacceptably big in some situations. The tests also shows that deflection on a flexible barrier is sensitive to the impact angle. It becomes obvious when you calculate the kinetic energy perpendicular to the barrier. At 110 km/h and 20°-angle, the perpendicular speed towards the barrier is 38 km/h, which equals about 1/9th of the kinetic energy in forward motion. Compared with the 80 km/h, 45°-angle test, where the kinetic energy is 50% of the forward motion.

The W-beam barrier has a lower deflection than the wire-rope barrier, but it is still more flexible than the concrete barrier and could thus be preferred when the expected impact angle is great and the situation only admits small deflection. The tests showed that the W-beam barrier could be suitable both as a roadside barrier and as a mid-barrier, as long as the combination of expected crash angles and travel speed does not create a situation leading to high injury risks.

In Sweden the wire-rope is used as a mid barrier (SNRA) on a 35- km, 13 -m wide road with previously frequent severe and fatal accidents. The accidents were predominantly frontal impacts caused by vehicles using the opposite lane e.g. for overturning. Since the wire-ropes were installed, there have been no severe injuries or fatalities on this road (ref?). In this case there are two driving lanes in one direction and one in the opposite direction, alternating every 2nd kilometre. The possibility of great impact angles is small, so the flexible barrier seems to work under these circumstances.

An important issue in these types of impacts is the triggering of the restraint systems. The crash pulse in different barriers differs regarding the pulse duration and the deceleration levels in the beginning of the crash phase. Ydenius (et al, 1998) showed variations in the airbag deployment in car-to-car impacts and in roadside impacts. The difference in these impact types was in the steepness of the pulse shape in the first 33 ms of the crash. In crashes with the mean acceleration of up to 10g, the share of deployed airbags was 50% higher in car-to-car impacts than in roadside impacts with lower acceleration in the first 33ms of the crash pulse. In the W-beam barrier test deployment of the airbags was delayed. The reason could be local forces on the sensor or too low acceleration for the sensors in the beginning of the crash phase. The delayed timing of the airbag deployment could lead to a higher risk of out-of-position.

The tests demonstrated the large variation of pulse duration and acceleration that can be observed in crashes with guard rails depending on the design of the guard rail. This variation highlights the need for further research regarding triggering for interior safety systems. It may be wise to trigger seatbelt pretensioner in crashes with low acceleration and high Δv , while airbags should deploy at higher accelerations.

The number of impact angles and impact speeds was a limitation in these test series. It would be preferable to get knowledge about the impact severity and dummy readings, also about the dynamic behaviour of the vehicle in more crash situations. In further studies it is necessary to investigate how vehicles of different mass and structure are influenced in crashes into different barrier types. It is not possible to draw many conclusions about the injury risk with a specific type of barrier, when only one car model was tested.

CONCLUSION

To achieve a moderate impact severity, a certain deflection of the barrier is necessary even for rather small impact angles.

The usability of wire rope has a big potential in several complicated situations and is useful for a wide range of impact angles.

The concrete barrier could be used in areas where you can not accept any deflection, and where the combination of expected angles and travel speed will not create a situation where the injury risk is too high.

W-beam barrier shows a good behavior in both tests and can be possible too using also as mid barrier.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support by the all sponsors of this joint research project;

AUTOLIV Research, Sweden
Folksam Insurance Group, Sweden
Monash University, Australia
RACV, Australia
Swedish National Road Administration
The National Society for Road Safety
TAC, Australia
VICROADS, Australia
Laverton Airforce Base, Australia

REFERENCES

1. Kommunikationsdepartementet. (1997). A route to a society with safe road traffic. Selected extract from memorandum prepared by the Ministry of Transport and Communications, Ds 1997:13, Sweden
2. Kullgren, A. (1998). Validity and reliability of vehicle collision data: Crash pulse recorders for impact severity and injury risk assessment in real-life frontal impacts. Karolinska institute, Stockholm, Sweden
3. Malm S. Krafft M, Kullgren A, Ydenius A. Vad karaktäriserar bilolyckor med döds och invaliditetsfall och hur kan de förhindras?, Presentation at the seminar "Tylösandsseminariet", Halmstad, Sweden, 1999

4. SNRA, Swedish National Road Administration, Utvärdering av alternativ 13 m väg, Report from VTI (Swedish National Road and Transport Research Institute) notat 67-2000
5. Tingvall, C. and Lie, A. (1996). The implications of the zero vision on biomechanical research. Proceedings of 1996 International IRCOBI Conference on the Biomechanics of Impact, September 11-13, Dublin Ireland 1999
6. Wayne, T. et al Highway Safety Appurtenances—Successes and Failures, 27th Annual Proceedings, American Association for Automotive Medicine, October 3-6, 1983, San Antonio, Texas
7. Ydenius A, Kullgren A, Pulse Shapes and Injury Risks in Collisions with Roadside Objects: Result from Real-Life Impacts with recorded Crash Pulses, Proceedings of 1999 International IRCOBI Conference on the Biomechanics of Impact, September 23-24, Sitges, Spain,

Appendix A

Concrete barrier



Figure 1 Test vehicle - 20° concrete barrier test.

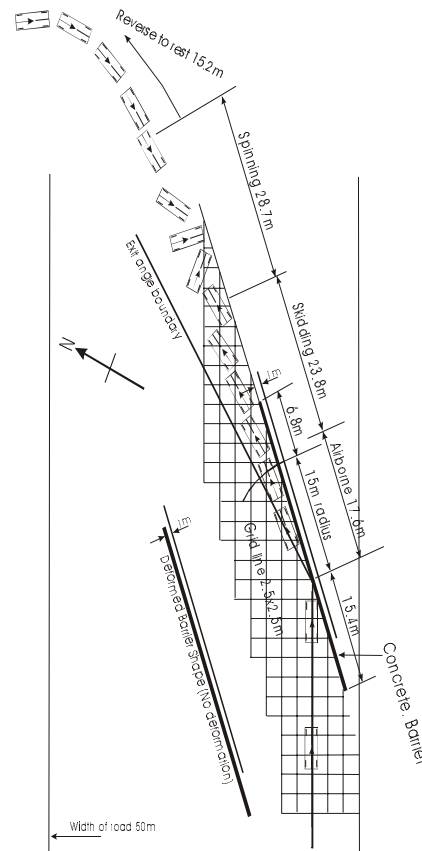


Figure 2. Vehicle trajectory
20° concrete barrier test.



Figure 3. Test vehicle - 45° concrete barrier

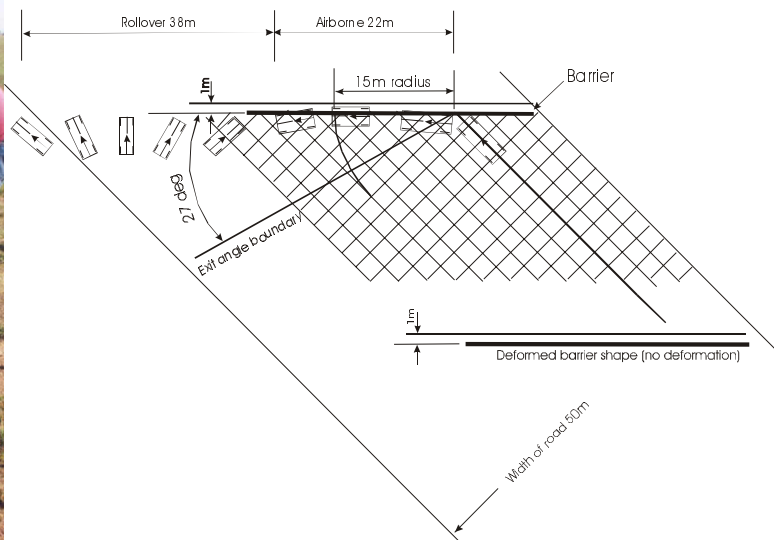


Figure 4. Vehicle trajectory - 45° concrete barrier test

Wire rope barrier



Figure 5. Test vehicle - 20° wire-rope test.



Figure 6. Wire rope condition after crash.

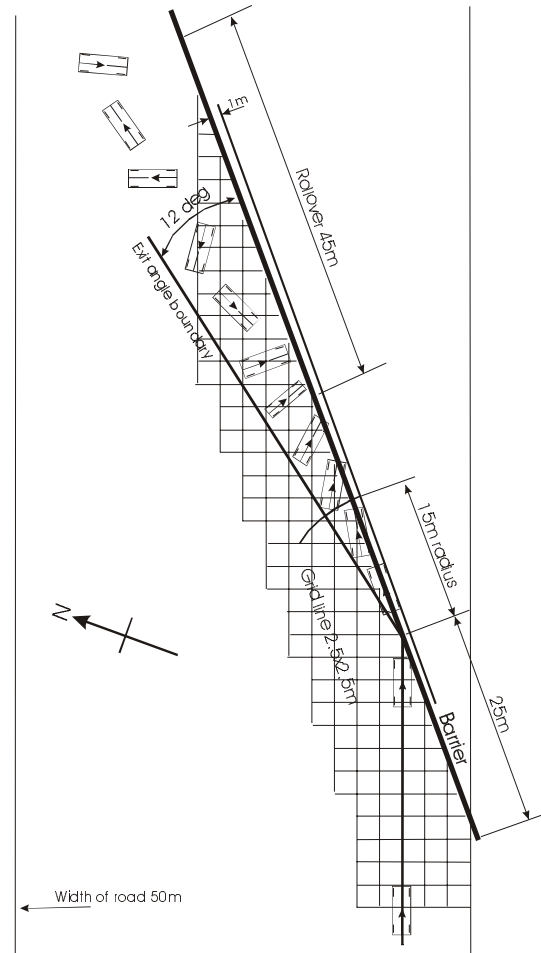


Figure 7. Vehicle trajectory - 20° wire-rope test.

Wire rope barrier



Figure 8. Test vehicle - 45° wire-rope test.



Figure 9. Wire rope condition after crash.

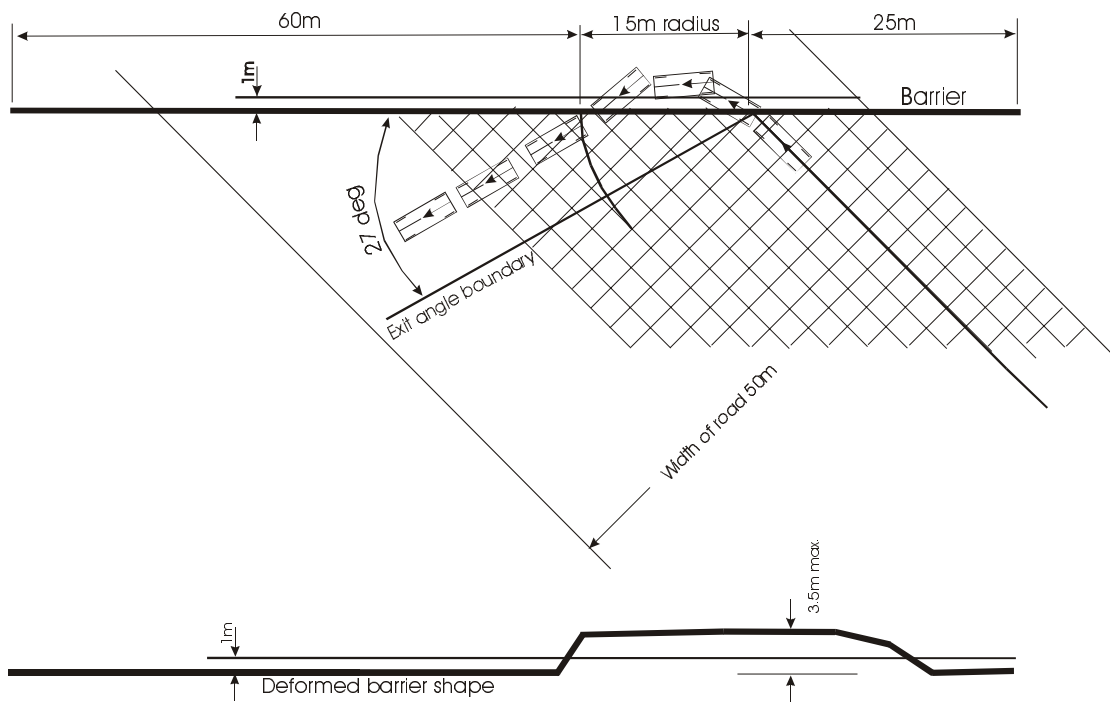


Figure 10. Vehicle trajectory - 45° wire-rope test.

W – beam barrier



Figure 11. Test vehicle - 20° W-beam test



Figure 12. W-beam barrier condition after crash.

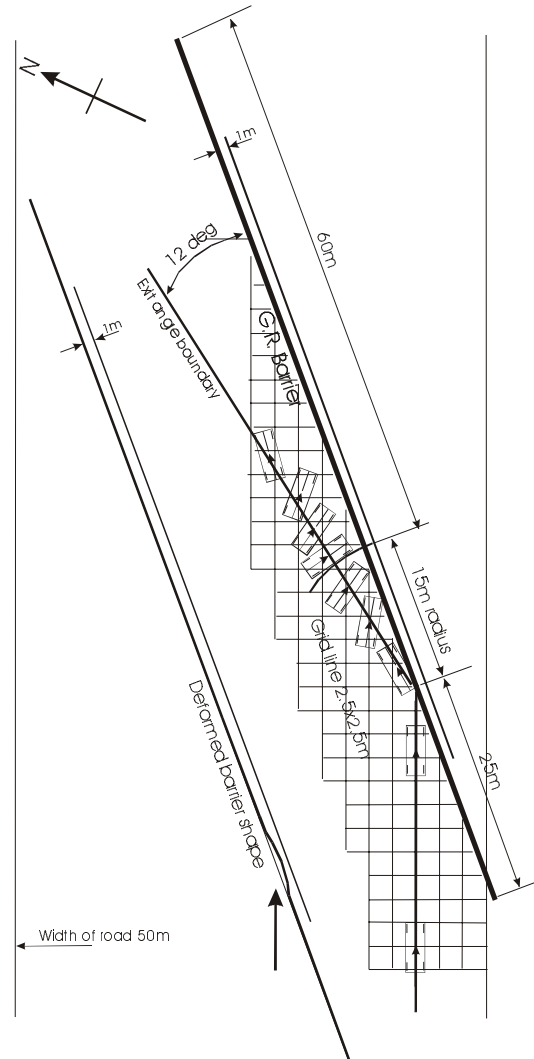


Figure 13. Vehicle trajectory - 20° W-beam test.

W-beam barrier



Figure 14. Test vehicle - 45° W-beam test



Figure 15. W-beam barrier condition after crash.

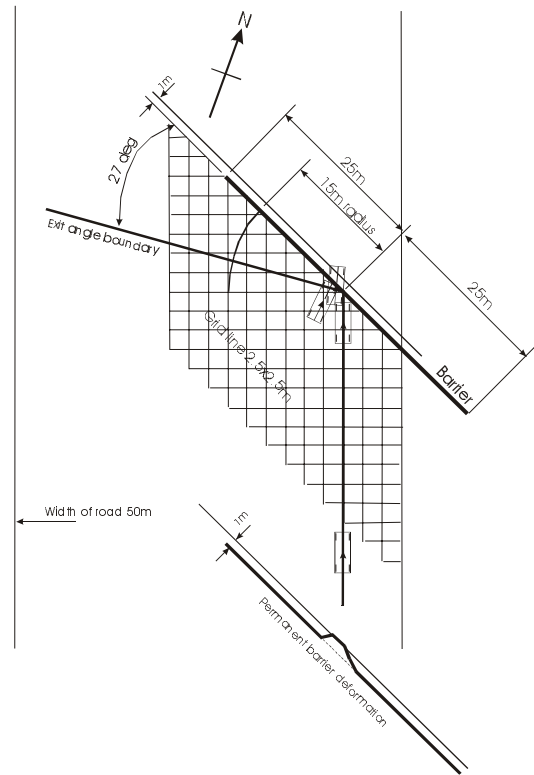


Figure 16. Vehicle trajectory - 45° W-beam test.